THE BENEFITS AND RISKS OF FEDERAL FUNDING FOR SEMATECH

The Congress of the United States
Congressional Budget Office

NOTE AND CREDIT

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PREFACE

Sematech is a proposed industrywide research consortium aimed at advancing the technology with which semiconductors are manufactured. The Congress will soon decide whether the federal government will participate in the consortium, and what form that participation would take. In response to a request by the Senate Commerce Committee, this paper analyzes the potential benefits and risks of federal involvement in Sematech. In keeping with the Congressional Budget Office's (CBO's) mandate to provide nonpartisan analysis, no recommendations are made.

The report was written by Philip C. Webre of CBO's Natural Resources and Commerce Division under the supervision of Everett M. Ehrlich and Elliot Schwartz. Peter Glick, Andrew Horowitz, Colleen Loughlin, Lisa Najarian, and Susan Punnett provided valuable research assistance. The author wishes to thank Thomas Dorsey, Wayne Glass, W. Edward Steinmueller, Richard Van Atta, and James Whitt for helpful comments. The report was edited by Sherry Snyder, assisted by Nancy H. Brooks. Kathryn Quattrone typed the manuscript and prepared it for publication.

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GLOSSARY

The following definitions of terms are based on Daniel Okimoto, Takuo Sugano and Franklin Weinstein, eds., *Competitive Edge: The Semiconductor Industry in the U.S. and Japan* (Stanford, Calif.: Stanford University Press, 1984), and Department of Commerce, Industry and Trade Administration, *A Report on the U.S. Semiconductor Industry* (September 1979). One very good guide to semiconductors is the September 1977 issue of *Scientific American*, which was devoted entirely to microelectronics.

Application-specific integrated circuit (ASIC) — An integrated circuit designed for one narrow use, such as substituting one large integrated circuit for many small ones. Often custom or semi-custom.

Bipolar — One of the two types of transistors and integrated circuits; the other is metal-oxide semiconductor (MOS). They are faster than MOS devices but more difficult to make.

Bit — A zero (0) or one (1) in the binary language of computers.

Byte — Eight (8) bits.

Captive producer — A semiconductor manufacturing firm that produces exclusively for in-house consumption. Contrasts with merchant producer.

Custom circuit	An integrated circuit designed and manufactured for a particular customer. Contrasts with semi-custom, which has only the last few manufacturing steps tailored to customers' specifications. Also contrasts with integrated circuits of standard design, which are produced in volume for many users.
Die	The small piece of the wafer on which an individual semiconductor device has been formed.
Diffusion	A semiconductor manufacturing process in which desired impurities are introduced into the silicon by baking the silicon wafers at high temperatures and pressures in chemically altered atmospheres. A less precise alternative to ion implantation.
Digital integrated circuit	An integrated circuit that uses binary codes (0's and 1's) to store and manipulate data by using the on/off properties of transistors. Contrasts with linear integrated circuits.
Diode	A discrete semiconductor device that allows electricity to flow only in one direction.
Dynamic random access memory (DRAM)	A type of RAM that requires some external support circuitry. Contrasts with static random access memory. Categorized by speed and memory capacity.
Epitaxy	A semiconductor manufacturing process in which a layer of silicon is grown on the surface of a silicon wafer. This new layer is grown because it possesses a unique crystalline structure or other desirable feature not found on the wafer itself.

Erasable programmable read only memory (EPROM)	A memory device that can be read but not written to. Unlike other programmable memories, it can be erased (by exposing it to ultraviolet light) and reprogrammed.
Etching	A semiconductor manufacturing process in which acid is used to remove previously defined portions of the silicon oxide layer covering the wafer to expose the silicon underneath. Removing the oxide layer permits the introduction of desired impurities into the exposed silicon through diffusion or ion implantation.
Gallium arsenide (GaAs)	A compound semiconductor material that allows transistors and integrated circuits to operate much more rapidly than similar devices made of silicon. Much more difficult, and hence more expensive, to manufacture than silicon.
Gate array	A kind of semi-custom circuit.
Geometries	The size of the smallest feature on an integrated circuit, usually the connections between transistors. At present, most new integrated circuit designs have geometries between 1.0 and 1.5 microns, although some new memory devices have smaller geometries.
Integrated circuit (IC)	A complete electronic circuit, composed of interconnected diodes and transistors, fabricated on a single semiconductor substrate, usually silicon. Also called a chip.

Ion implantation	A semiconductor manufacturing process in which the silicon is bombarded with high-voltage ions in order to implant them in specific locations and provide the appropriate electronic characteristics. A more precise alternative to diffusion.
Linear integrated circuit	An integrated circuit that creates and processes an internal analog of the signal it is receiving. Contrasts with a digital integrated circuit which reduces the signal to a series of 0's and 1's. Used typically in consumer goods, communications equipment, and scientific instruments.
Lithography	A semiconductor manufacturing process in which the desired circuit pattern is projected onto a photoresist coating covering the silicon wafer. When the resist is developed, like an ordinary photograph, selected portions of the resist come off, thus exposing parts of the wafer for etching and diffusion.
Logic circuit	A type of digital integrated circuit that performs certain logical or mathematical functions and often provides connections between other major parts of computers.
Memory device	An integrated circuit that stores binary data. Categorized according to accessibility (at random or serially), size, speed, and to whether it can be written to or is read only.
Merchant producer	A semiconductor manufacturing firm that produces primarily for sale on the open market. Contrasts with captive producer.

Metal-oxide semiconductor	One of the two types of transistors and integrated circuits; the other is bipolar. It is simpler to fabricate and hence is often used in manufacturing large, dense integrated circuits. On the other hand, it is slower than bipolar and sensitive to radiation, which limits its military applications.
Metalization	A semiconductor manufacturing process in which a layer of metal, such as aluminum, is placed on the wafer to connect the transistors and diodes within an integrated circuit.
Micron	A micrometer, or one-millionth of a meter.
Microprocessor	An integrated circuit that performs the function of a central processing unit of a computer.
Optical lithography	Lithography that uses ordinary or ultraviolet light to expose the circuit pattern. Currently the most commonly used technology. Contrasts with X-ray lithography.
Photomask	The template (usually made of quartz) containing the circuit pattern that is used in lithography to define the areas for etching in the photoresist.
Photoresist	A light-sensitive chemical used to coat silicon wafers during lithography. The photoresist makes the wafer like a photographic negative. The integrated circuit pattern is projected onto the coated wafer, and then the wafer is developed.

Photovoltaic cell	A specialized diode that turns light into electricity. Used in space and other remote applications. Becoming common in some consumer uses.
Random access memory (RAM)	A memory device whose individual memory cells can be read from or written to at random (that is, not serially).
Read only memory (ROM)	A memory device whose contents can be read from but not written to.
Semiconductor	A material that is neither a good insulator nor a good conductor; usually silicon, germanium, or gallium arsenide. The term has come to refer to all devices made of semiconducting material, including integrated circuits, transistors, and diodes.
Semi-custom circuit	An integrated circuit that has the initial phases of its fabrication standardized, but allows the later stages to be tailored to suit the individual customer.
Silicon	A semiconducting material commonly used in semiconductor devices because it is so easy to work with.
Static random access memory (SRAM)	A type of RAM that has self-contained memory circuitry. Contrasts with dynamic random access memory. Categorized by speed and memory capacity.
Synchrotron	A type of particle accelerator being discussed as a potential source of X-rays for use in X-ray lithography.

Transistor	A three-terminal semiconductor device used mainly to amplify or switch. Its invention at Bell Laboratories in 1948 started the semiconductor revolution.
Wafer	When most semiconducting material is purified, it comes out in long sausages between 1 and 8 inches in diameter, which are then sliced into wafers, roughly 1 millimeter thick. The wafer is then used as the substrate for forming semiconductor devices.
Wafer stepper	A type of lithography equipment that exposes the wafer one die at a time, instead of the whole wafer at once.
X-ray lithography	An emerging type of lithography that uses X-rays instead of light to expose the circuit patterns on the wafer.

SUMMARY

Observers within and outside the U.S. semiconductor industry have called for a response by the federal government to the perceived declining competitiveness in that industry. The centerpiece of these proposals for federal action is Sematech--a research consortium of U.S. semiconductor producers and suppliers of semiconductor manufacturing equipment. As currently envisioned, Sematech would receive almost half its funding from the federal government--a total of about $600 million over the next six years. The aim of Sematech is to improve the manufacturing technology of the U.S. semiconductor industry (particularly that used in the production of integrated circuits), an area of widely acknowledged weakness. The Sematech proposal raises many important issues; one set of questions centers around the public interests at stake and whether federal intervention is warranted or appropriate; another set centers around whether Sematech would address these interests.

THE SEMATECH PROPOSAL

Current plans for Sematech center on a six-year, $1.5 billion, three-phase effort. The intent is to improve the equipment, materials, and techniques involved in the manufacturing process, as opposed to improving the design of semiconductor devices themselves. A production line will be built to prove and integrate the technology, but actual full-scale manufacturing is left to individual semiconductor companies. Sematech's near-term focus is on improving current commercial practices rather than on developing entirely new materials or technology for the industry.

Funding for the consortium would come from private firms and from federal, state, and local governments. Membership by private firms is limited to U.S. capital-affiliated semiconductor companies and semiconductor manufacturing equipment (SME) producers. Member companies are expected to account for roughly half the total funding. The federal government would contribute about $100 million annually, and the state and local governments in which the Sematech facility is located are also expected to contribute. The goal of Sematech is to have commitments of roughly $250 million per year for the next six years.

Sematech has three tasks. The first is to conduct research and development (R&D) on advanced semiconductor manufacturing techniques. The second is to test and demonstrate the resulting techniques on a pilot production line. Third, Sematech would then develop processes to adapt these proven techniques so that they can be applied to the manufacture of a wide variety of other products.

The technology developed by Sematech will be given first to member firms, but will be licensed for a royalty after a suitable delay. The results will become more widely available as makers of semiconductor manufacturing equipment incorporate them into their products, and the technology will eventually spread to all semiconductor manufacturing firms, at home and abroad. Thus, the benefit to the member firms would be to have a head start on using the technology, not absolute monopoly of that technology.

THE SOCIETAL BENEFITS OF SEMICONDUCTOR PRODUCTION

The federal government traditionally relies on markets to decide how and when industries will grow and contract. Proponents of Sematech must therefore demonstrate that without federal intervention, the level of resources devoted to semiconductor research and development will be inadequate to meet society's needs. In essence, proponents must identify some type of public benefit associated with semiconductor production that accrues to the national economy but not just to individual semiconductor firms. Identifying these public benefits is somewhat subjective, but at least three types can be advanced:

- National security;
- Research and development spillovers to the whole semiconductor industry; and
- Spillovers to the economy as a whole, and, more generally, to the national science infrastructure.

National Security

U.S. military strategy relies on having fewer, but technologically more advanced, weapons than the Soviet Union. The concern of military planners is that deterioration of U.S. semiconductor producers could soon lead either to dependence on foreign sources for components for sophisticated weapons systems, or to a decline in the technological base needed to develop and use these components. Domestic production facilities dedicated to semiconductors with military applications could be procured to overcome any dependency on foreign suppliers. If, however, the ability to use the technology is lost, such facilities would be irrelevant to future generations of semiconductor technology. The alternative--using either devices made by foreign firms or devices produced in the United States under foreign license--may reduce the flexibility of U.S. foreign policy or may compromise the U.S. advantage in military technology. Sematech may have a role to play in maintaining a sound and up-to-date technological base.

Spillovers Within the Industry

From the semiconductor industry's perspective, investing in innovative design research often brings a greater return than focusing R&D efforts on better manufacturing processes. Many firms spend a great deal of effort duplicating (or "reverse engineering") products manufactured by other companies. The existence of these so-called imitators reduces the incentives for innovative firms to perform R&D. Such firms may underinvest in R&D because a substantial part of the benefits from their discoveries might be captured by imitators. Moreover, this pattern biases the investment choices made by U.S. semiconductor firms toward R&D projects that produce radical new devices with proprietary designs and may discourage these firms from investing in manufacturing technology, the results and benefits of which are relatively easy for others to appropriate. Federal funding could fill the investment gap in generic manufacturing technologies from which all semiconductor producers may benefit.

Spillovers to the Economy

Recent economic studies have suggested that the rate of return to society of R&D in electronics has been much greater than the return to the individual firms performing it. This evidence is consistent with case studies of innovation in other industries, which have suggested that R&D's return to society is, on average, twice that of the private return. In fact, acknowledgement of these societal benefits is reflected in the large amount ($400 million to $500 million) that federal agencies currently spend on semiconductor R&D. But most of this research is related to technologies that have either distant commercial applications (such as the use of gallium arsenide materials) or only military significance (such as radiation hardening, which allows semiconductors to function during nuclear warfare).

Science-based industries, such as the semiconductor industry, play a role akin to that of universities in building and preserving the nation's stock of human capital--that is, both scientific and engineering knowledge and the ability to expand it. The U.S. semiconductor industry thus not only creates new technology but also helps diffuse this knowledge throughout the economy.

The future of manufacturing technology will depend increasingly on the use of semiconductors in the production process. Robotic technology, for example, relies on semiconductors, as does "statistical" process control, which depends entirely on the rapid absorption, transmission, and analysis of information on production lines via semiconductors. Flexible manufacturing systems depend on electronic computers and other equipment that can be reprogrammed easily yet can perform complex tasks with precision. Thus, semiconductors are not only being incorporated into more goods, but, more to the point, they are affecting the ways in which more goods are being made.

EVALUATING THE PROGRAM

The value of the Sematech program depends on the answers to a series of questions, including:

- Would the program address the semiconductor industry's competitive shortcomings?

- Would it do so in a way that provides benefits to the economy or society in general?

- What risks does such a program present? and,

- How might the design of the program affect its ability to generate the expected social benefits?

By focusing on manufacturing technology, Sematech would be addressing an area in which the U.S. industry lags its competitors and in which existing incentives may be inadequate to encourage individual firms to conduct research that might help them catch up to those competitors. Improving manufacturing technology would lower the cost of these devices. Lower costs in turn would facilitate the application of semiconductors to other areas, such as robotic manufacturing, telecommunications equipment, and computers and other electronic goods. Although the effects of Sematech on national security would be less direct and less immediate, over the long term the military would certainly benefit from the competence of the manufacturing base fostered by Sematech.

Does Sematech Address the Industry's Problems?

It is generally agreed that the weakness of the U.S. semiconductor industry is found in manufacturing technology rather than the production of any specific devices. Thus, Sematech's focus on generic manufacturing equipment and techniques seemingly brings new resources to bear on a problem that is not being adequately addressed by either federal or private research programs. Semiconductor manufacturers spend only about $200 million to $300 million on R&D to improve their manufacturing technology. Makers of semiconductor manufacturing equipment spend another $500 million. The $250 million budgeted for Sematech's research therefore would raise spending on R&D for commercial semiconductor manufacturing in the United States by about one-third.

Does Sematech Create Public Benefits?

Sematech addresses the three areas of federal interest outlined above--national security, spillovers within the semiconductor industry, and spillovers to the economy--although to different degrees. National security goals are met by assuring an adequate supply of specific devices that are produced domestically. But Sematech cannot guarantee that U.S. semiconductor producers will suddenly find filling U.S. military requirements a profitable activity, especially considering the Defense Department's stringent bureaucratic and technological requirements that often have no civilian counterpart. Sematech, however, may increase the probability that any given technology needed by the military will be available from U.S. sources in the future.

Sematech's prospective benefits, however, should be greater in the diffusion of knowledge and new techniques, both within the semiconductor industry and to other industries. Many economists have expressed concern that research into new products proceeds more rapidly than research into improving production processes. The traditional counterargument is that equipment manufacturers have strong incentives to incorporate technological advances into the machines that they sell, and these advances are thereby incorporated into production lines. But many producers of equipment for making semiconductors are specialized and small, particularly when compared with semiconductor manufacturers themselves; they may not be able to afford significant product research. Thus, semiconductor manufacturing research may well be substantially underfunded from a societal point of view, and the societal rate of return on such research may be correspondingly high.

Moreover, improvements in manufacturing processes would lower the cost of producing all semiconductors and enhance the existing U.S. advantage in this industry--that of design--by making them more price competitive. Lower prices would allow sophisticated applications of microelectronics to diffuse more rapidly through the economy. The potential benefits of the Sematech program from an economywide perspective, therefore, may be substantial.

What Are the Risks?

A research program like Sematech bears the conventional risk associated with scientific experimentation--success is far from guaranteed. But given the likelihood that Sematech would attract highly knowledgeable and experienced personnel from its member firms, this risk should be no greater, and could be less, than that associated with a comparable private endeavor.

Sematech as a policy instrument, however, poses other risks. The most important risk concerns the rate of diffusion of Sematech's results. If those results diffuse too slowly, the program's benefits would be usurped by its member firms. But many avenues are available for disseminating findings of this type--personnel movements, professional journals and meetings, word-of-mouth, and, of course, by building these results into new semiconductor manufacturing equipment. The primary concern may be, instead, that Sematech's results would be disseminated too rapidly and become readily available to foreign producers, undermining the purpose of the program. To counter this problem, foreign firms could be refused formal access to its results (although this action might set an undesirable precedent for future trade policy). But even with rules regarding membership and access, results might be spread abroad by U.S. firms with foreign production facilities, or by U.S. SME producers who incorporate Sematech's results into their equipment and then sell it to foreign producers. Sematech's contribution to the national welfare may be reduced if U.S. capital-affiliated firms take its federally financed results and deploy them in foreign production sites.

A separate risk is that of collusion--agreements among firms to restrict trade--which is always a concern whenever firms in the same industry meet for a common purpose. Sematech could lead to collusion, for example, if its member firms were to use it as a vehicle for redefining the conventional standards for microelectronic products. Such action could create serious disadvantages for nonmember firms and provide benefits only to Sematech members. But if Sematech tried to enforce a standard that was not accepted by the market, its efforts might prove self-defeating. Given the likely diffusion of Sematech's research, however, the consortium would probably not become a barrier to competition in the semiconductor industry.

A third risk concerns centralizing the industry's research agenda. Although an industrywide consortium avoids the costs of duplicative research by individual firms, it entails the risk of creating a less diverse research program than would occur if individual firms were to spend the same level of resources. Individual firms, however, would probably not spend as much on research and development in the absence of Sematech because of the likelihood that their results would be appropriated by competitors. Thus, the research effort in Sematech may complement the R&D of individual companies and need not detract from their other research efforts.

A final risk concerns the unprecedented institutional arrangements found in Sematech. Industrywide research consortia are proving to be a popular new arrangement, but their track record is short and mixed. Similar projects have either had some measure of success--as the Microelectronics and Computer Technology Corporation has--or have had problems maintaining their cohesion, as did the semiconductor industry's Operation Leapfrog in the early 1980s. The magnitude of the financial and personnel commitments being made to Sematech, however, indicate that its members will be committed to its success.

A separate but related issue is whether the federal government will be able to stay within its role as a "silent partner." Once basic policy guidelines have been established, the government's role will be largely advisory. In many other applied research endeavors that the government funds, it determines the technological agenda (as it does in the programs of the National Aeronautics and Space Administration and the National Institutes of Health that deal with commercial technologies). But the success of Sematech may depend on the government's taking a more passive role in daily affairs.

ISSUES IN POLICY DESIGN

The design of the Sematech program will influence greatly its prospects for generating economic benefits. An immediate issue is the royalty (licensing) policy it will pursue. From a societal perspective, Sematech will succeed to the extent that its research results are spread quickly throughout the domestic industry but are slow to reach foreign producers. In practice, however, it would be difficult to channel the dissemination process, since the avenues through which technology diffuses are often the same in the United States and abroad. Moreover, it may be viewed as inequitable to give domestic firms, who had the opportunity to participate in Sematech but did not join, preferential access to its results.

The more general concern is that U.S. firms will use Sematech to increase the productivity of their foreign subsidiaries that export to the United States and thereby accelerate the movement of the semiconductor industry abroad. Inhibiting this trend may require a more detailed agreement between the government and the industry, rather than a simple royalty policy.

An additional issue is the precedent that Sematech establishes. Supporting technological advancement may be a better form of assistance to an industry than restraining trade through tariffs or